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Resonant Γ–X-transfer in GaAs/AlAs quantum-well structures

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Abstract. We investigate the Γ_2–X_{z1} intersubband dynamics in GaAs/AlAs quantum-well structures by time-resolved infrared pump and probe experiments. In the studied structure, the second Γ-level in GaAs is nearly resonant to the first X_z-level in AlAs. We observe a biexponential decay of the bleaching signal with a fast time constant in the order of 1 ps and a second slower time constant of about 7 ps at 10 K and 4 ps at 300 K, respectively. The long term decay represents the X_z–Γ_2 transfer by elastic Γ–X scattering at low temperatures. At 300 K electron-LO-phonon-scattering accelerates the Γ–X transfer.

Introduction

Investigation of intersubband carrier dynamics is very important for application of quantum well structures as infrared devices. In particular, GaAs/AlAs structures are promising candidates for infrared photodetectors (QWIPs) [1] and quantum cascade lasers (QCLs) [2]. As these structures have extreme deep quantum wells (∼ 1 eV) the dark current in QWIPs is strongly reduced and the operating temperature in QCLs is increased. However, in GaAs/AlAs quantum well structures intersubband dynamics not only occurs in the Γ-valley of the GaAs layers but also the AlAs barriers, which are the quantum wells for X-electrons, have to be considered. At the heterointerface Γ–X-mixing takes place, that significantly influences the intraband carrier dynamics [3]. Recently, a laser scheme with strong population inversion between mixed Γ and X states in GaAs/AlAs-structures has been proposed in [4].

1. Sample structure and experimental method

The investigated GaAs/AlAs quantum well structure consists of 100 layers with 10 nm wide GaAs quantum wells embedded in between 2.5 nm thick AlAs layers. The central 5 nm of the wells are doped by silicon with a concentration of 6×10^{17} cm^{-3}. The structure is grown by MBE on a semiinsulated GaAs (100) substrate. According to our band structure calculations the first excited Γ-state in GaAs is nearly in resonance with the ground X_z state in AlAs and Γ–X-mixing occurs (see Fig. 1(a)), corresponding to an overlap integral $S_{\Gamma X} = |<\psi_{\Gamma 2} \mid \psi_{X1}>|^2 = 0.03$.

The relaxation measurements are performed by a Nd:glass laser system of 8 Hz repetition rate with two travelling wave IR dye lasers and two difference frequency mixing stages [5]. The system generates two pulses of 2 ps duration and a spectral width of 10 cm^{-1} independently tunable between 800 cm^{-1} and 2500 cm^{-1}. One of the two infrared pulses excites electrons at a well defined pump frequency $\tilde{\nu}_{\text{pump}}$ from the ground subband to the excited subbands. The subsequent change of the intersubband absorption is measured time-resolved by the second weaker infrared pulse at $\tilde{\nu}_{\text{probe}}$.

2. Results and discussion

The absorption spectra shown in Fig. 1(b) represent the transition between the Γ_1- and the Γ_2-state which has a strong Γ-character at small k [see Fig. 1(a)]. At 10 K the peak frequency is located at 915 cm^{-1}. At higher temperatures the typical redshift and broadening of the absorption lines from 50 cm^{-1} at 10 K to 73 cm^{-1} at 300 K are observed. The absorption $\alpha L = -\ln T$ decreases from 2.5 at 10 K to 1.5 at 300 K.

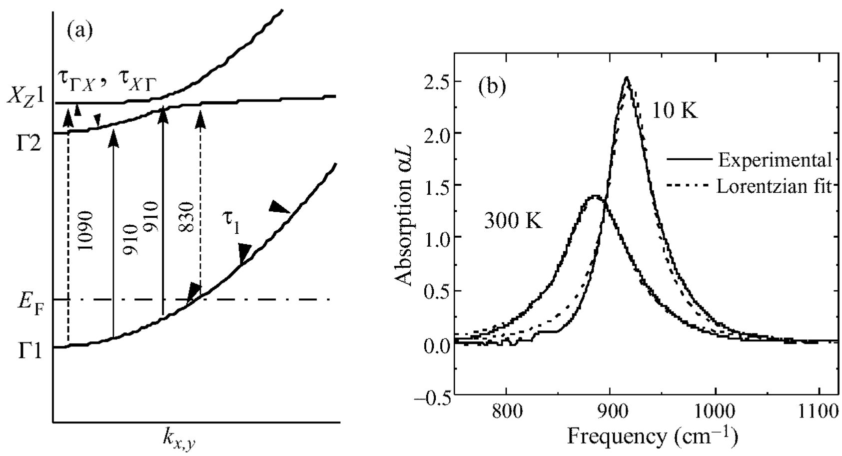

Fig. 1. (a) Schematic conduction band dispersion for the GaAs/AlAs QW structure in the presence of Γ–X-mixing. Arrows indicate the possible transitions at $T = 10$ K. (b) Intersubband absorption spectra.

Pump and probe measurements at different pump frequencies with a probe frequency at the Γ_1–Γ_2 resonance are compared for $T = 10$ K [6] and $T = 300$ K. For $T = 10$ K the transmission changes at $\tilde{\nu}_{\text{probe}} = 910$ cm^{-1} are plotted in Fig. 2 after excitation at

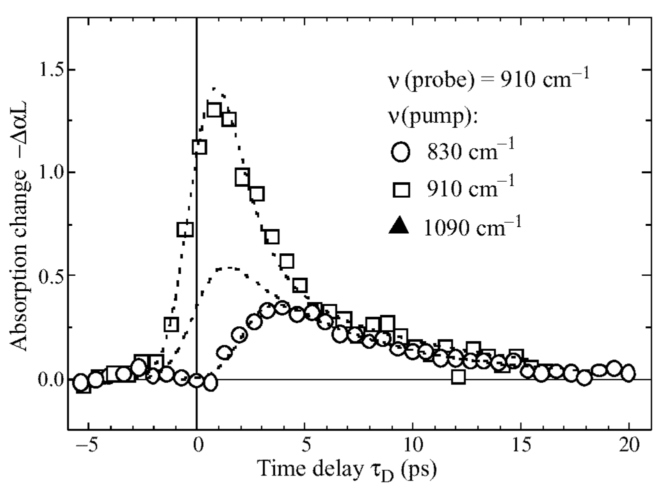

Fig. 2. Time resolved absorption change at $T = 10$ K after excitation at different pump frequencies. Dashed lines are fits of the experimental data by solving rate equations.

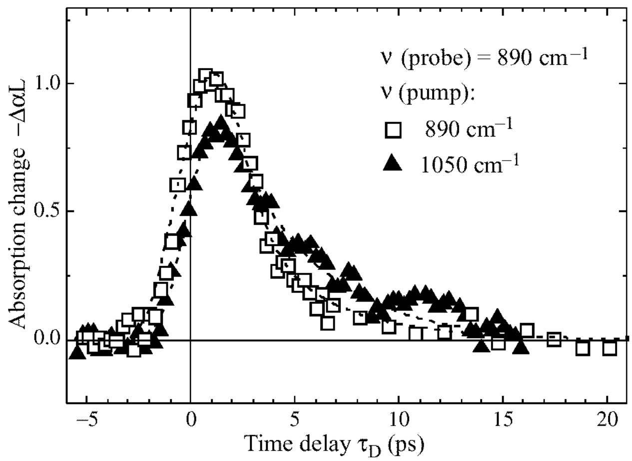

Fig. 3. Time resolved absorption change at $T = 300$ K after excitation at different pump frequencies. Dashed lines are fits of the experimental data by solving rate equations.

$\tilde{\nu}_{\text{pump}} = 830$, 910 and 1090 cm^{-1}. Excitation in the center of the intersubband absorption line at 910 cm^{-1} occupates Γ and X_z states [see Fig. 1(a)] and leads to a biexponential behavior of the relaxation signal with a fast relaxation time $\tau_1 = 1.2$ ps and a long term decay $\tau_2 = 7.0$ ps. In contrast, pumping at 830 and 1090 cm^{-1} excites states with strong X_z character and a decay dominated by the long relaxation time τ_2 is found. This observation can be explained by a rapid $\Gamma_2 \rightarrow \Gamma_1$ recovery time τ_1 together with long term carrier scattering processes between the nearly resonant Γ_2- and X_{z1}-valleys, which are strongly coupled [3]. For $T = 300$ K the transmission changes at $\tilde{\nu}_{\text{probe}} = 890$ cm^{-1} are shown in Fig. 3 after excitation at $\tilde{\nu}_{\text{pump}} = 890$ and 1050 cm^{-1}. Similar to the measurements at low temperature two relaxation times are observed. Pumping in the center of the absorption band we obtain two time constants, 1 ps for the fast decay and about 4 ps for the long term decay. The curve for the pump frequency of 1050 cm^{-1} only shows the long relaxation time.

For a detailed interpretation of the results the energy dispersion diagram of the studied structure is considered [Fig. 1(a)]. Under excitation, the electrons fill the Γ–X-mixed subbands. Due to the Γ–X interaction at the heterointerface direct transitions to the X_{z1}-subbands become possible. Absorption of light due to Γ_1–X_z transitions was already detected in GaAs/AlAs quantum-well structures previously [1]. Thus for intense excitation in and around the absorption peak, both Γ_1–Γ_2 and Γ_1–X_{z1} optical transitions take place. As the energy dispersions for Γ and X electrons are strongly different, the absorption band for intervalley transitions must be broader than that for Γ–Γ transitions. Consequently, in spite of the weak oscillator strength of the Γ_1–X_{z1} transition, it dominates the absorption change at pump frequencies at the feet of the absorption line, where the absorption coefficient for the Γ_1–Γ_2 transition is negligibly small. On the other hand, intervalley scattering processes play a key role in carrier relaxation. After excitation, electrons are redistributed among the second Γ-subband and the X_z-subband and vice versa. Electron-LO-phonon scattering and elastic electron scattering due to the interface mixing potential (Γ–X_z mixing) are relevant mechanisms for the Γ–X transfer in GaAs/AlAs type II superlattices [3, 7]. In our sample electron-LO-phonon scattering is believed to be of minor importance at low temperature, because the separation of the coupled Γ_2- and X_{z1}-subbands (about 15 meV)

is below the optical phonon energy. Therefore, the elastic electron scattering due to the interface mixing potential is expected to dominate the transfer process between the Γ_2 and X_{z1}-states of the AlAs barrier at 10 K [8]. At 300 K also electron-LO-phonon-scattering becomes possible due to the increased phonon occupation probability and a shorter time constant τ_2 is observed.

Electrons return from AlAs to GaAs mainly via the Γ_2-subband, as transitions into the Γ_1-subband are suppressed because of the smaller overlap integral. The X_1–Γ_2 relaxation time $\tau_{X\Gamma}$ can be determined for pump frequencies at the feet of the absorption line, when electrons are directly excited into subband states with strong X_{z1} character. Due to the lower density of states in the Γ-valley compared to the X-valley X–Γ scattering times $\tau_{X\Gamma}$ are longer than Γ–X scattering times $\tau_{\Gamma X}$.

Modell calculations using rate equations show the best fit with $\tau_1 = 0.8$ ps, $\tau_{\Gamma X} = 2.5$ ps and $\tau_{X\Gamma} = 4.5$ ps for $T = 10$ K and $\tau_1 = 0.6$ ps, $\tau_{\Gamma X} = 2.0$ ps, $\tau_{X\Gamma} = 2.5$ ps for $T = 300$ K, respectively [6].

3. Conclusion

We have directly observed the influence of Γ–X mixing on intersubband relaxation in a GaAs/AlAs quantum-well structure. The resonant intersubband carrier transfer from the Γ valley in GaAs to the X_z valley in AlAs and vice versa, has been observed at 10 K. At room temperature an additional electron-LO-phonon-scattering channel enhances the transfer rates.

References

[1] H. C. Liu, P. H. Wilson, M. Lamm, A. G. Steele, Z. R. Wasilewski, Janmeng Li, M. Buchanan and J. G. Simmons, *Appl. Phys. Lett.* **64**, 475 (1994).
[2] C. Becker, C. Sirtori, H. Page, G. Glastre, V. Ortiz, X. Marcadet, M. Stellmacher and J. Nagle, *Appl. Phys. Lett.* **77**, 463 (2000).
[3] H. C. Liu, *Appl. Phys. Lett.* **51**, 1019 (1987).
[4] V. Y. Aleshkin and A. A. Andronov, *JETP Lett.* **68**, 79 (1998).
[5] I. M. Bayanov, R. Danielius, P. Heinz and A. Seilmeier, *Optics Commun.* **113**, 99 (1994)
[6] S. R. Schmidt, E. A. Zibik, A. Seilmeier, L. E. Vorobjev, A. E. Zhukov and U. M. Ustinov, *Appl. Phys. Lett.* **78**, (2001) to be published
[7] J. Feldmann, J. Nunnenkamp, G. Peter, E. Göbel, J. Kuhl, K. Ploog, P. Dawson and C. T. Foxon, *Phys. Rev. B* **42**, 5809 (1990).
[8] O. E. Raichev, *Phys. Rev. B* **49**, 5448 (1994).